Improvements in the residual OH emission removal in SINFONI pipeline spectra

Andrea Modigliani[1], Richard Davies[2], Christophe Dumas[3] and Mark Neeser[1]

[1] ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
`amodigli@eso.org`,
[2] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany
[3] ESO, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile

1 Introduction

The strong and variable OH air-glow emission lines in the 1-2.5 μm spectra impose severe restrictions on the observing strategy. This is particularly true for instruments using Integral Field Spectroscopy techniques to sample the sky, as they are characterized by a narrow field of view.

SINFONI is the Spectrograph for INtegral Field Observations in the Near Infrared (1.1-2.45 μm) at the ESO-VLT. SINFONI was developed and built by ESO and MPE in collaboration with NOVA. It is an integral field spectrograph which combines Near Infrared spectroscopy and adaptive optics in a field of view that is image sliced [1], [2]. It is mounted at Yepun, the fourth Unit Telescope (UT4) of the ESO-VLT and has been operational since April 1st, 2005. SINFONI operations are supported by a data reduction pipeline [3], as part of the Data Flow Operations [4].

The standard SINFONI observational strategy is to do a sequence of object-sky observations to sample the object and the sky at regular intervals. This observing technique is limited temporally by changes in the flux of the OH lines on time scales of 2-3 minutes, spectrally by variations in the flux among individual OH lines, and by instrument flexures which may result in spectral format shifts, which can lead to P-Cygni type residuals.

These effects are indeed present in some spectra generated by early pipeline releases and triggered the development of an improved algorithm that can correct them. As part of a collaboration between ESO and MPE, we have implemented in the SINFONI pipeline an algorithm originally developed by the MPE to solve these problems. In this paper we present the first results of the new algorithm.

2 Sky emission

Near infrared air-glow emission originates in OH radicals which are created by reactions between ozone and hydrogen high in the atmosphere. Removing the emission lines which result from the subsequent radiative cascade is a crucial part of processing near infrared (1-2.5 μm) spectra.

This problem is relevant as it has been proven that the strongest OH lines, which lie in the H band, have fluxes of the order of 400 photons m^{-2}arcsec^{-2}. This contrasts strongly with the background continuum measurable between lines of only 590 photons m^{-2}arcsec$^{-2}\mu$m^{-1}. This means that even at moderate spectral resolutions (R $\approx$ 3000), like the one of SINFONI, the background level on an OH line can be more than three orders of magnitude higher than the level between the lines.

Due to temporal changes in the absolute flux in OH sky lines exposure times are usually limited to 2-3 minutes. This sets a lower limit to the statistical photon noise. An additional source of problems is the peculiar change of absolute flux in OH lines, in which the (vibrational/rotational) bands of lines vary with respect to one another. Finally the effects of instrumental flexures, which are typical of instrument rotation in a Cassegrain or Nasmyth telescope configuration, may lead to P-Cygni type residuals.

While long-slit spectrographs, using a slit length much longer than the object of interest may prevent such problems by allowing an appropriate fit of the residual sky background, integral field spectrographs like SINFONI, with very limited FOV, impose constraints on the observations and require more sophisticated data reduction techniques.

3 Algorithm

More details on the algorithm to remove residual OH emission from near infrared spectra can be found in [5] or in the SINFONI pipeline User Manual at http://www.eso.org/pipelines.

In a nutshell the algorithm allows one to find a scaling as a function of wavelength that can be applied to a spectrum from a sky cube, in order to match it optimally to the sky background in an object cube. This scaling function is then applied separately to the spectrum at each wavelength position of the sky cube, creating a modified sky cube. This modified cube is then subtracted from the object cube.

The scaling function may be found by taking into account that the main contribution to the OH lines is coming from vibrational and rotational transitions, with the former contributing the most. Transitions between vibrational bands lie within well defined wavelength limits, with only a small amount of overlap between different vibrational transitions. Thus, to a first approximation one may divide the spectrum into sections corresponding to specific vibrational transitions and treat these separately.

The sky residual correction algorithm is outlined in the following steps:

- The wavelength ranges which correspond to the different vibrational and rotational transitions of the OH emission lines are defined.

- The noise associated with the object frame is calculated.
- Object intensities more than two times the object's noise above the background are flagged.
- Sky pixels are identified, flagged, and selected as good sky pixels when they make up at least a given fraction (this can be defined by the user and is set to 80% by default) of the spectrum.
- The average object and sky spectra are calculated. For each plane in the cube (both object and sky) an average is computed by excluding pixels which are more than three sigmas above the median. This defines the object and sky intensity.
- The thermal contribution to the sky background is estimated and subtracted from the sky spectrum. To improve accuracy, as the sky spectrum contains many emission lines, we first smooth this spectrum with a running box and then fit a Boltzmann function (see Fig. 1, left panel).

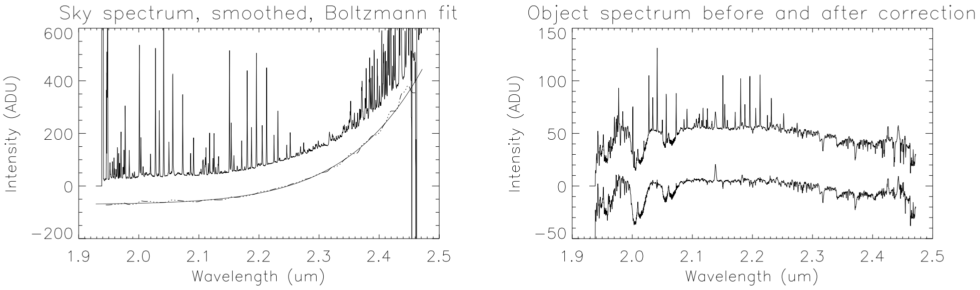

Fig. 1. On the left panel are shown the sky background, its smoothed profile and the fit by a Boltzmann function, for clarity shifted down by 50 ADU. On the right panel we compare un-corrected and corrected sky subtracted object spectra which for clarity are shifted down by 50 ADU. Rotational transitions affect the spectrum quality by only 1-5%. Not only can one see 1-0S(1) at 2.12 um and Br$_\gamma$ at 2.17 μm, but now the H2 1-0Q(1) and 1-0Q(3) emission lines are clearly seen longward of 2.4 μm, and several CO band-heads are also visible at 2.3-2.4 μm.

- To properly compute the shift between object and sky only wavelengths corresponding to vibrational or rotational transitions are considered. This removes the effect from improper spectrum features.
- The pixel shift between the sky and the object spectra is computed by cross correlating the two spectra and the sky spectrum and the sky cube are correspondingly shifted.
- The scaling factor that is applied to the sky emission lines in order to remove them from the object spectrum is computed.

  The object and sky sub-spectra are extracted over wavelength ranges corresponding to each vibrational transition. A scaling factor is computed for each range. As a first approximation, this factor is derived from the

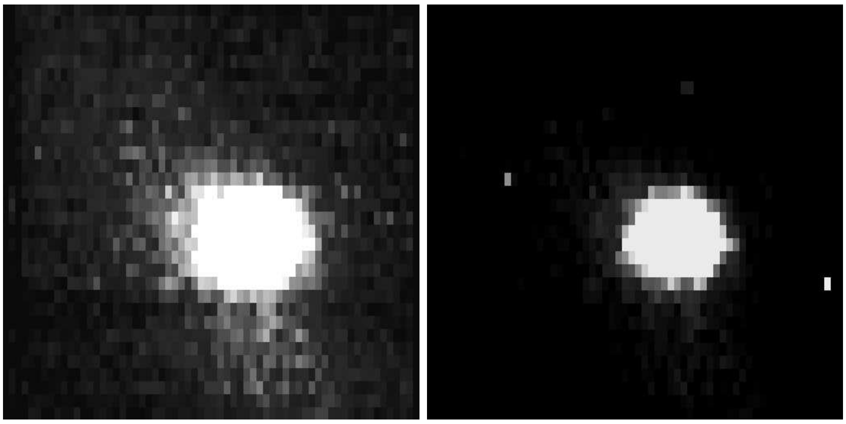

Fig. 2. Un-corrected (left) and corrected (right) object cubes. The cube plane corresponding to 2.151 μm is shown. Input data included a dedicated sky frame. The image on the left has the same intensity scale as the image on the right.

line contributions only due to the vibrational transitions. Then the recipe computes a scaling factor based on the contribution of the rotational transitions. Later the two factors are combined and the shifted sky spectrum is accordingly rescaled and subtracted from the object spectrum, to obtain an object spectrum cleaned of sky lines (see Fig. 1, right panel).

- The shifted and scaled sky cube is finally subtracted from the object cube. The resulting cube is thus corrected for the sky residuals (see Fig. 2, right panel).

4 Summary

We have described an algorithm in the SINFONI pipeline which allows the correction of residual sky lines, possibly present in the extracted object. For a large set of data the accuracy in the estimation of the thermal background (which affects the definition of the continuum level) is 1%, and the sky line residuals, after correction, improve by a factor of 40 in comparison to their values before the application of this new algorithm.

References

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